Interpretation of Central Loop EM Soundings near Geologic Contacts

EM 2.4

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Summary

In an earlier paper (Wilt et. al.,1986) we showed that for the central-loop sounding method a horizontal component of the magnetic field develops near geologic inhomogeneities. The horizontal field was found to be impulsive and to decay exponentially at late-time. In this report we show how for simple classes of two-dimensional models the conductivity or conductance of a discontinuous surface layer can be determined from the horizontal field data. We also show how the anomaly from a surficial contact layer may be removed to reveal anomalies from deeper sources. Data for the study were acquired with a scale model system.

For models that approximate a truncated thin-sheet,the conductance and the distance to the edge can be determined from two adjacent soundings. The conductance of the surficial layer can be found by determining the velocity of the horizontal field temporal peak from two adjacent soundings with the aid of the relationship $S = 2/\mu V$, where V is the velocity of the peak, μ is the magnetic permeability and S is the conductance of the sheet. The late-time slope of the horizontal field decay curve is proportional to the conductance of the sheet and the distance to the contact. If the conductance is obtained from the velocity calculation then the distance to the edge can be obtained from the late-time slope.

The anomaly from a surface contact may be removed from central-loop sounding data for two-dimensional surficial contact models. This is accomplished by first determining the conductance of the surface contact layer and distance to the edge. A set of normalized correction curves are then used to compensate the soundings for the edge effect. The curves are obtained by measuring the vertical gradient of the horizontal component over a thin-sheet contact model. Using Ampere's law we show that the vertical gradient of the horizontal field is equal to the horizontal gradient of the vertical field in the direction of the contact. The integral of this last quantity over the length of the profile constitutes the edge effect. The correction curves are obtained by numerically integrating the gradient data over the length of the profile. The contact correction is applied to a particular sounding by simply adding the contact corrections for a particular conductance and distance to the edge to the observed data. Applying the correction curves to some scale model data we were able to almost completely compensate for the contact anomaly.

Introduction

Wilt et. al., (1986) examined a number of EM sounding configurations and found that the central-loop system data was was the least distorted by lateral inhomogeneities and that it therefore allowed the most reliable one-dimensional interpretation. It is known that the horizontal magnetic field at the center of the loop is zero for homogeneous or layered models and is only observed near geologic inhomogeneities. It thus is an indicator of the presence of such features.

In the earlier paper we suggested that the shape and character of the horizontal fields may be related to the dimensions and conductivity of geologic inhomogeneities. In this report we examine this relationship for some two-dimensional contact models and show how the conductivity or conductance of a discontinuous surface layer may be determined by an analysis of the measured horizontal fields. We also show how in some circumstances the contact effect can be stripped from the overall response to reveal anomalies related to deeper bodies. The data for this study was acquired with a scale model system described in Wilt et. al., (1986).

Horizontal Fields

For a loop source, a step change in current induces azimuthally symmetric currents with respect to the source position if the medium is homogeneous or horizontally layered. In these cases the magnetic field at the center of the loop is vertical. Near geological inhomogeneities, however, this symmetry is lost and the field at the center of the loop also exhibits a horizontal component. In the case of a two-dimensional inhomogeneity, the horizontal field is directed towards the structure and the time and spatial characteristics of the field are related to the conductivity and geometry of the structure.

Figure 1 shows profiles of the horizontal fields over the contact model for observation times that range from .1 millisecond (ms) to 7 ms after transmitter current shut-off. These curves show that the horizontal fields are sharply peaked at the earlier observation times but they are broader, lower in amplitude, and have zero-crossings at later times. We find that the peak amplitude,anomaly half-width and the positions of the peaks are related to the dip and conductance of the contact layer as well as the depth of the overburden.

The analysis of the horizontal fields near a contact simplifies considerably if the geology may be approximated by a truncated conductive thin sheet. A thin sheet has the characteristic of a uniform current density across its thickness. At late times the magnetic fields for sheets with finite thickness often closely resemble those for thin sheets because the current density is approximately uniform. For contact models, the time range when a particular model may approximate a thin sheet contact is dependent on the conductance and the distance to the contact. An approximate formula for this time is given by Dallal (1985),

$$t > 2\mu RS \tag{1}$$

where t is the time after current shut-off in seconds, μ is the magnetic permeability in H/m, S is the conductance of the layer ($S = \sigma h$) in Siemens, and R is the distance to the contact in meters.

Determination of Conductance and Distance from the Contact

In Figure 2 we plot horizontal field decay curves on a semilogarithmic plot at distances of 200, 500, and 700 meters from the contact for the model given in Figure 1. We can see that the curves have well defined peaks and linear late-time slopes. The transient curves for stations close to the edge have sharp peaks occurring early in time and have steep late-time slopes; stations further from the contact peak at later times and show gentler late-time slopes.

In Figure 3 we plot the position of the horizontal field transient peaks against time for several surface contact models. At later times the curves are linear with slopes inversely proportional to the conductance of the sheet. The slopes of these curve define the velocity of the temporal peak of the horizontal field transients; We have empirically found that this velocity is given by,

$$V = \frac{2}{\mu S}. \tag{2}$$

We note that this is exactly one-half the velocity of the induced current ring in an infinite thin-sheet model (Grant and West, 1965). This suggests that the temporal peak may be related to induced currents that have migrated to the edge and have been reflected back. This model is inconsistent, however, with the late-time behavior of these transients which can be represented by an exponential function. This is typical of confined bodies not the unconfined current flow suggested by this reflection model (Spies,1980).

By using the velocity as determined from Figure 3 we can estimate the conductance of the contact layers using equation (2). The calculated values for all but the thickest models agree to within 15 percent of the true value. Note that for stations close to the edge the thin sheet approximation is invalid and the horizontal field peaks do not migrate linearly with time. They initially travel faster at early time before approaching a constant velocity at later time.

The late-time slopes of the decay curves are also useful in estimating contact parameters. Dallal (1985) showed that on a semi-logarithmic plot the late-time slope of the horizontal field decay curve has a constant slope, suggesting that it can be represented by a simple exponential function. The form of this function is given by,

$$H_x(t) = H_0 e^{-\frac{t}{\tau}} \quad , \quad \tau = \frac{\mu S R}{3} \tag{3}$$

where τ, the time constant, is proportional to the conductance of the layer and the distance from the contact. If we know the conductance of the contact layer (from equation 2, for example) then this formula allows us to compute the distance to the contact. Applying this formula to the curves shown in Figure 3 we can determine the distance to the edge with an accuracy of about 10 percent.

Contact Stripping

In Wilt, et. al., (1986) we showed how the presence of a surface contact can distort sounding data making it difficult to either determine the properties of any horizontal layers or to see through them to prospect for deeper bodies. It would be advantageous to remove this effect from the sounding so that the deep structure could be properly resolved. With the central-loop method it is possible to separate the contact effect from other anomalies and remove it from the data.

To properly interpret a vertical magnetic field sounding the contact effect must be separated from the observed data.

$$H_{z\ corr}(t) = H_{z\ obs}(t) - H_{z\ contact}(t) \tag{4}$$

For a central-loop sounding at a distance R from a contact, this may be written,

$$H_{z\ corr}(t) = H_{z\ obs}(t) - \int_R^{\infty} \frac{\partial H_z(t)}{\partial R} dR \tag{5}$$

where $\partial H_z(t) / \partial R$ is the derivative of the vertical field in the direction of the contact. For the central-loop configuration both the transmitter and receiver move for each sounding so it is not clear that the horizontal derivative of the vertical field can be approximated by taking the difference between adjacent soundings and dividing by the separation, even if they are closely spaced. We must therefore derive an alternate expression to equation (5) to correct for the contact effect.

For two-dimensional structures, we can apply Ampere's law to derive a relation between the horizontal and vertical components of the magnetic field.

$$\nabla X\ H = J \tag{6}$$

In rectangular coodinates, if we denote the y direction as the strike of the contact, then we can use equation (6) to write the derivatives of the field components for the current in this direction,

$$\frac{\partial H_x(t)}{\partial z} - \frac{\partial H_z(t)}{\partial x} = J_y .$$

In the air above the model, however, the current is zero so this expression reduces to,

$$\frac{\partial H_x(t)}{\partial z} = \frac{\partial H_z(t)}{\partial x} . \tag{7}$$

This relation suggests that the vertical derivative of the horizontal field may be substituted for the horizontal derivative of the vertical derivative in equation (5) to remove the contact effect.

Our strategy for using this expression is first to obtain $\partial H_x(t) / \partial z$ in generalized coordinates that include the conductance, S, of the surface contact layer and the distance to the contact, R. From these curves a set of correction curves can be derived by numerically approximating the integral in equation (5). This correction term can then be added to the observed data to remove the effect of the surface contact. To apply these corrections to a field sounding, we must first use the method described above to obtain the conductance S of the contact layer and the distance R from the contact.

If we plot $\partial H_x(t) / \partial z$ for thin sheet models against a normalized distance, given by $R_n = \mu S R / t$, then all of the profiles for the thin sheet models collapse to a single set of curves. We can use these curves to obtain a set of correction curves by approximating the integral in equation (5) using Simpson's rule.

Next, we test this scheme by applying it to some scale model data. We correct all the stations on a profile, sounding by sounding, to remove the contact effect from the data. Figure 4a shows early and middle-time vertical field profiles for a thin sheet contact model. Figure 4b shows the same profiles but with the contact correction applied. The corrected profiles show little effect of the contact except for some noise at the earliest times and for stations adjacent to the contact. In these cases the finite difference approximation for $\partial H_x(t) / \partial z$ is probably not very accurate.

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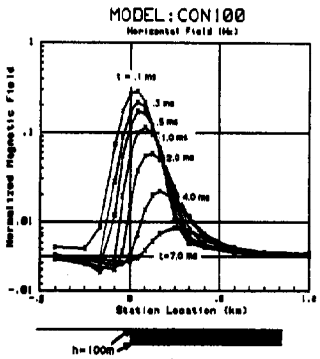

FIG. 1. Central loop horizontal magnetic field time profiles over contact model shown at bottom of figure.

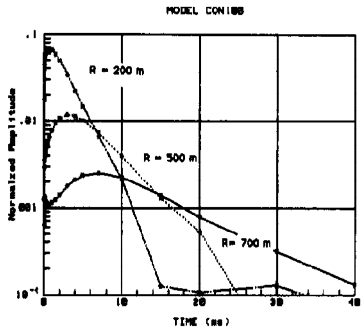

FIG. 2. Horizontal field decay curves for soundings 200 m, 500 m, and 700 m from contact model in Figure 1.

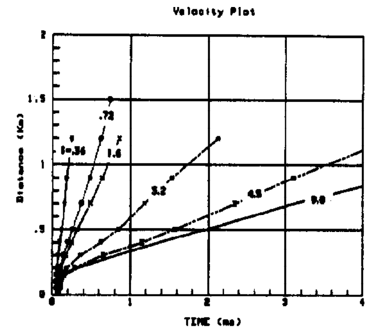

FIG. 3. Migration of horizontal field transient peaks for thin sheet models.

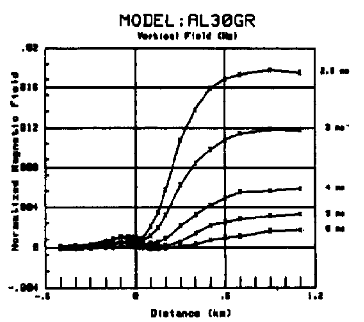

FIG. 4a. Vertical magnetic field time profiles over a contact model.

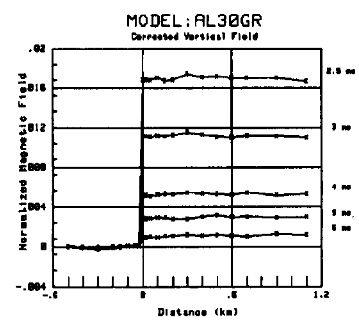

FIG. 4b. Vertical magnetic field time profiles with contact correction applied.